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Definition of CCS Provinces with Multi-criteria and Least Cost Path Analysis

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Abstract

The concept of CCS Provinces is introduced, referring to the region where a CO_2 injection site is cost-effective based simultaneously on the cumulative transport and storage costs. The methodology implements, in a GIS tool, a linear cost model for pipeline construction considering local conditions that affect the pipeline cost. Multi-criteria analysis with those local factors, allows building cost surface maps representing the cost of a standardized diameter pipeline in any cell of the GIS model. The storage costs are assigned to the potential injection location and the resulting map is combined through map algebra with the transport cost surface. The CCS Province is defined using least cost path analysis to find for each cell in the GIS the lowest accumulative transport and storage cost and allocating to a given province all the cells that lead to the same storage site. The methodology is illustrated for the Iberian Peninsula and Morocco.

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Keywords: CCS provinces; transport and storage costs; GIS; Least cost path; storage and transport infrastructures.

1. Introduction

CO_2 transport costs by pipeline are dependent on geographical conditions, such as topography, crossing of water bodies and existing infrastructures, land use, etc., and are amenable to being minimized with geographic information systems that select the least-cost corridor. If the transport cost components are mapped for a given region, least cost-path analysis (LCPA) [1] can be applied to find the most economical transport route from source to sink.

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Several previous studies related to CO_2 pipelines networks have resorted, in some extent, to geographic information system (GIS) tools to find the location for least-cost routes between CO_2 sources and the potential injection sites, such as for case studies in the Netherlands [2] and China [3], and optimization of transport networks considering geographic constraints have also been presented for the United States of America [4] and Europe [5].

The use of LCPA in a GIS environment requires a cost formulation that can be minimized and a cost surface, usually created resorting to map algebra on a multi-criteria analysis (MCA) process. Thus, the cost formulation should identify clearly the GIS layers that are likely to influence the costs of building a pipeline at each location.

Previously adopted models to account for the pipeline investment costs (I_T) suited for the local conditions they were addressing, include the following for the Netherlands [2]:

$$I_T = B_C \cdot Ft_{lu} \cdot Ft_c \cdot D \cdot L \tag{1}$$

where B_c is the standardized cost factor (€/m^2), Ft_{lu} and Ft_c are, respectively, terrain factors for crossing different types of land-use and for following or deviating from existing pipeline corridors, D is pipeline diameter and L is pipeline length. This linear cost model takes into account the main geographical components influent to the cost of building a pipeline and allows to map the transport costs from CO_2 source to the suite of potential injection sites.

However, in the CCS technology chain, transport costs are usually a fraction of capture cost and even of storage costs. While capture costs are dependent on the technology options at facilities, and are not geographically dependent, CO_2 storage costs are dependent on site conditions, including variables such as depth of reservoir, injection rate, onshore/offshore location. These cost dependencies imply that proximity between CO_2 source and injection site is not necessarily an indicator of cost-effectiveness or a good criteria for source-sink match, and that storage capacity is also not a good enough criteria either, since the cumulative costs of transport and storage may indicate that, although enough storage capacity exist in a specific site, economic factors may choose a more distant injection site.

This article aims at presenting a methodology that resorts to MCA and LCPA in a GIS environment to integrate the geographically and geologically dependent transport and storage costs in cost-surface maps and to define CCS provinces that can be used as a planning tool for defining CCS transport and storage infrastructures. The CCS Province is defined by finding for each cell in the GIS the lowest accumulative transport and storage cost allocating to a given province all the cells that lead to the same storage site. The methodology is illustrated for the Iberian Peninsula and Morocco.

2. Methodology

The methodology (Fig. 1) implements, in an GIS tool, a linear cost model for pipeline construction considering local conditions that affect the pipeline cost, such as land-use, ground slope, crossings of infrastructures 8such as roads and railways) or other criteria thought adequate for a particular region. These local criteria are included as terrain factors that represent multiplying factors for the basic cost of building a pipeline. Thus, transport investment costs (I_{Tcell}) are simulated at each GIS cell according to the following linear model:

$$I_{Tcell} = B_c \cdot \prod_i F_i \left(\sum_n F_n \cdot A_n \right) \tag{2}$$

where B_c is the standardized cost factor, applicable to the entire cell, F_i are the cost factors that modify the value of B_c and are mapped uniformly over a cell, such as ground slope. F_n are the cost factors that do not apply over the entire area of a cell, such as crossing of existing infrastructures, and that apply only over a fraction, A_n, of the cell.

Cost factor maps and their integration into a final cost surface representing the expected investment cost for each cell are obtained through MCA and map algebra implementation of equation (2). CO_2 storage costs are included as a point based map, with the location of potential CO_2 injection sites and attributes required to define the main characteristics of the storage site. For each CO_2 injection site, investment and OMM costs are computed on the basis of location (onshore/offshore), depth, injection rate, and the number of wells required to inject the CO_2 volume transported by the standardized diameter pipeline, according to van den Broek, et al. [6]:

$$I_S = W\left(C_d H + C_w\right) + C_{sf} + C_{sd} \tag{3}$$

where: I_S – Storage investment costs; W - Number of wells per sink; C_d - Drilling costs per meter, H - the drilling depth, being the depth of the reservoir starting at the bottom of the sea (for offshore sites) or the ground surface (for onshore sites) plus the thickness of the reservoir; C_w - Fixed costs per well (in case of re-use of existing wells, these are the costs for the workovers of those wells to make the well suitable for CO_2 storage); C_{sf} - Investment costs for the surface facilities on the injection site and investments for monitoring (e.g. purchase and emplacement of permanent monitoring equipment; C_{sd} - Investment costs for the site development costs, e.g. site investigation costs, costs for preparation of the drilling site and costs for environmental impact assessment study. Monitoring investment costs in pre-operational phase are also included.

The storage costs are assigned to the potential injection location and the resulting map is added through map algebra to the transport cost surface resulting in an Integrated Cost Surface, representing the localized (at cell level) cost of transport and storage, that is, the cost for cost for transporting CO_2 per meter length of pipeline, and the cost for transport and store CO_2 in those cells where an injection well is defined.

LCPA over the integrated cost-surface allows the determination of the least cumulative cost distance to the nearest source over the integrated cost surface and from each cell to every injection site. Cost allocation is applied to assign each of the cells to the nearest (cost-effective) CO_2 injection site. The CCS Province is defined by all the cells that are cost allocated to a given CO_2 storage site, that is, the locations from which transport and storage of CO_2 would find the lowest costs for a network leading to the same storage site.

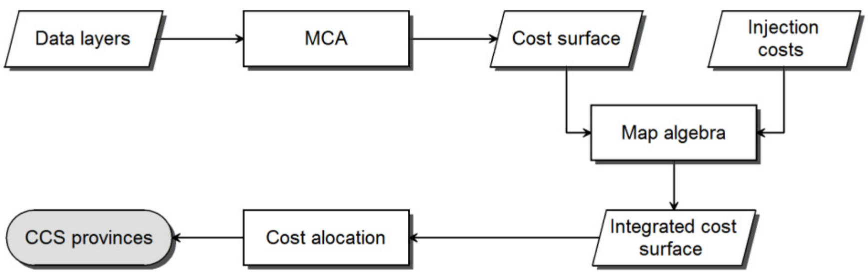

Fig. 1 – Flow diagram of the methodology.

3. Application to the Iberian Peninsula and Morocco

The methodology was applied to the Iberian Peninsula and Morocco. Within the scope of the FP7 COMET project [7], storage capacity in this region was estimated in nearly 30 Gt storage capacity, distributed through 163 possible storage sites and combined in 43 storage clusters (Fig. 2) and 285 stationary CO_2 sources were identified and grouped in 78 source clusters.

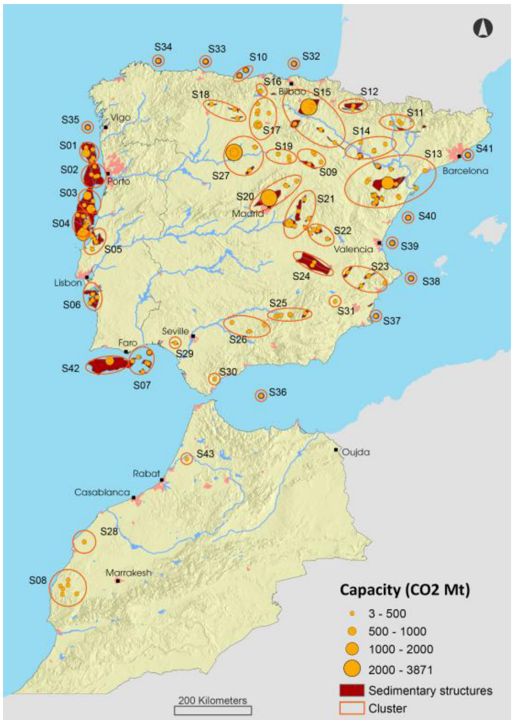

Fig. 2 –Storage clusters in the study area.

3.1. Transport cost model

The pipeline investment costs in each cell are calculated using the following linear model [8], a variant of the equation (2):

$$I_{Tcell} = B_c \cdot F_c \cdot F_s \, [\, F_{lu} \cdot (1 - 0.1N) + (0.1N \cdot F_{ci})] \tag{4}$$

The standardized cost factor, B_c, represents the cost for building a CO_2 pipeline onshore, in a terrain with a slope lower than 10%, in an unpopulated area, without crossing any existing infrastructure or using an existing pipeline corridor. The spatial information that was regarded likely to affect the standard pipeline building costs was grouped in four terrain factors: i) land use (F_{lu}); ii) terrain slope (F_s); iii) crossing (F_{ci}) of existing infrastructures (roads and railways and) and, iv) availability of corridors (F_c) where natural gas pipelines already exist. Terrain factors are, thus, a relative measure of cost. Whenever each of the spatial variables in a given cell deviates from the base conditions, a terrain factor differing from 1 is applied. The term (0.1N) accounts for the crossing of N infrastructures by a pipeline in 10% of the length of the cell. F_{ci} applies to 0.1N of the cell, with the remaining percentage (1-0.1N) being accounted in the land use terrain factor (F_{lu}) of the cell. The terrain factors and standardized cost factors applied in the COMET project are shown in Table 1 [9]:

Table 1 – Terrain factors and pipeline basic costs applied in the study area.

Designation	Description	Value
Standardized cost factor (B_c)	$€_{2010}/(m \times m)$	1357
Terrain Factors		
Land use (F_{lu})	Unpopulated	1
	Urban and associated areas	1.8
	Protected areas	10
	Cultivated land	1.1
	Forest	1.3
	Bare areas	1.1
	Regularly flooded	1.2
	Water bodies	4
Crossings (F_{ci})	Roads	3
	Railways	3
	High speed railways	3
Corridors (F_c)	Offshore (dev. from exist. pipelines)	3
	Offshore (fol. exist. pipelines)	2.7
	Onshore (fol. exist. pipelines)	0.9
	Onshore (dev. from exist. pipelines)	1.0
Slope (F_s)	<10%	1
	10-20%	1.1
	20-30%	1.2
	30-70%	3
	>70%	9

Map algebra with the surfaces representing the four terrain factors and the surface with the number of crossings, multiplied by the standardized terrain factor allows retrieving the **cost surface map** of pipeline investment costs in the study area (Fig. 3). Costs in each cell varies from 1221 €/(m×m) to values above to 6000 €/(m×m). The main influences to the cost variation are the environmental protected areas and the mountainous regions that occur in the three countries. The highest investment cost obtained was 122130 €/(m×m), associated to a cell located within a protected area and with a terrain slope above 70%, no crossings and no pipeline corridors, in which case the investment costs equation (4) reduces to $I_{cell} = B_c \cdot F_c \cdot F_s \cdot F_{lu} = 1357 \cdot 1 \cdot 10 \cdot 9 = 122130$ €/(m×m).

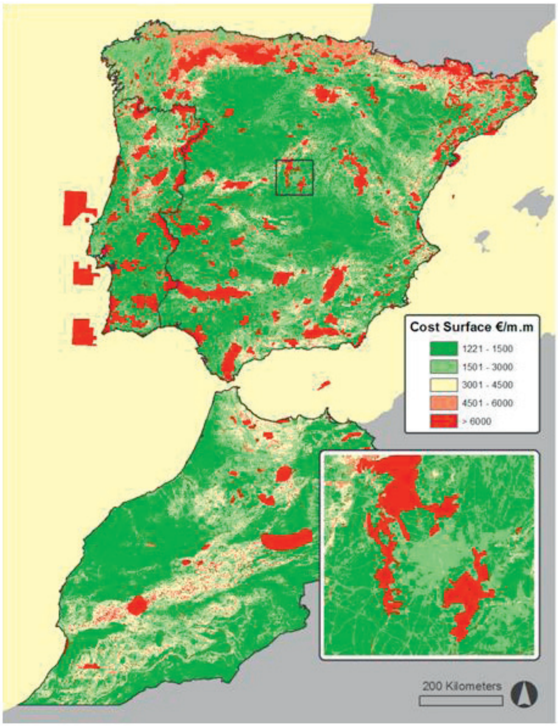

Fig. 3 – Cost surface map for transport of 1MtCO_2/a.

3.2. Storage cost model

The CO_2 storage costs vary strongly depending on the type of reservoir (saline aquifers, hydrocarbon fields), location (onshore, offshore), surface area that needs to be characterized/monitored or the previous existence of wells and/or facilities.

Within the COMET project, the investment costs for each specific storage site were estimated according to equation (3), based on van den Broek, et al. [6]. For each potential CO_2 injection site, the investment costs were estimated on the basis of reservoir depth, thickness, storage capacity and injection rate. In some circumstances, for large injection sites, many injections wells may be admissible and multiple facilities surface facilities were considered (one surface facility for each 10 injection wells). Table 2 lists the value assigned to each CO_2 storage cost component in equation (3), with the exception of the number of wells and injection rate which were estimated resorting to several analytical solutions [10-13] and considering parameters such as depth, permeability, radius of influence of wells, rock compressibility, interference between wells, etc., for an admissible pressure build-up of 20% of the initial reservoir pressure.

Table 2 – Storage costs components and basic costs [7].

Cost component	Onshore aquifer	Offshore aquifer[1] (WD<60 m)	Offshore aquifer (60m<WD<100m)	Offshore aquifer (100m<WD<1000m)
Site development costs (C_{sd})	24 480 k€	24 097 k€	24 097 k€	24 097 k€
Drilling costs per meter (C_d)	4 k€	10 k€	18 k€	26 k€
Well fixed costs (C_w)	0 k€	8 200 k€	8 200 k€	8 200 k€
Surface facilities[2] (C_{sf})	1 530 k€	61 200 k€	61 200 k€	61 200 k€
Monitoring investments	1 530 k€	1 530 k€	1 530 k€	1 530 k€
OMM[3]	5%	5%	5%	5%

[1] WD – depth to sea bottom
[2] On surface facility per each 10 injection wells
[3] Operating, Maintenance and Monitoring (OMM) costs are given as a % of investment costs.

Investment costs, computed according to equation (3) and normalized per annual injection rate, vary as shown in Fig. 4 for the 163 sites that compose the 43 clusters.

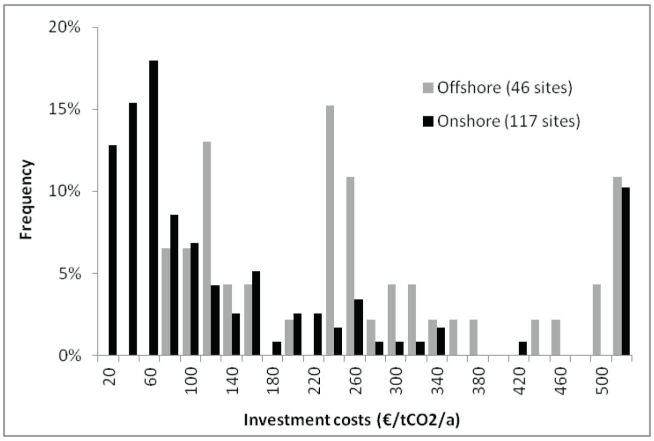

Fig. 4 – Distribution of storage costs per injection rate for potential storage sites.

3.3. Integration of cost surfaces

The storage costs per cluster were added to the transport cost surface, with the cost assigned to the GIS cell corresponding to the cluster hub. The modified cost surface map represents the local (cell size) transport cost and storage (where an injection cell exists) given the local conditions. The total pipeline investment costs between any source and storage cluster is the sum of the costs associated to each cell along which the pipeline path. That is, it adds the costs for each cell in equations (3) and (4), according to:

$$I_T = D \cdot L \cdot \sum B_c \left\{ F_c \cdot F_s \cdot \left[F_{lu} \cdot (1 - 0.1N) + 0.1N \cdot F_{ci} \right] + I_s \right\} \quad (5)$$

where L is pipeline length and D is pipeline diameter. In order to find the least-cost path between source and storage clusters, this equation was minimized with LCPA.

The cost-distance map in Fig. 5a was calculated with equation (5) to find the least accumulative cost distance from each cell to the nearest (least-cost) of the 43 storage clusters over the integrated cost surface. Finally, cost allocation was applied to define the suite of locations that lead to the same storage clusters, defining the area where it is cost-effective to transport and store CO_2 to a specific cluster, i.e., the zone of influence of the storage site and what is here designate as CCS province (Fig. 5b).

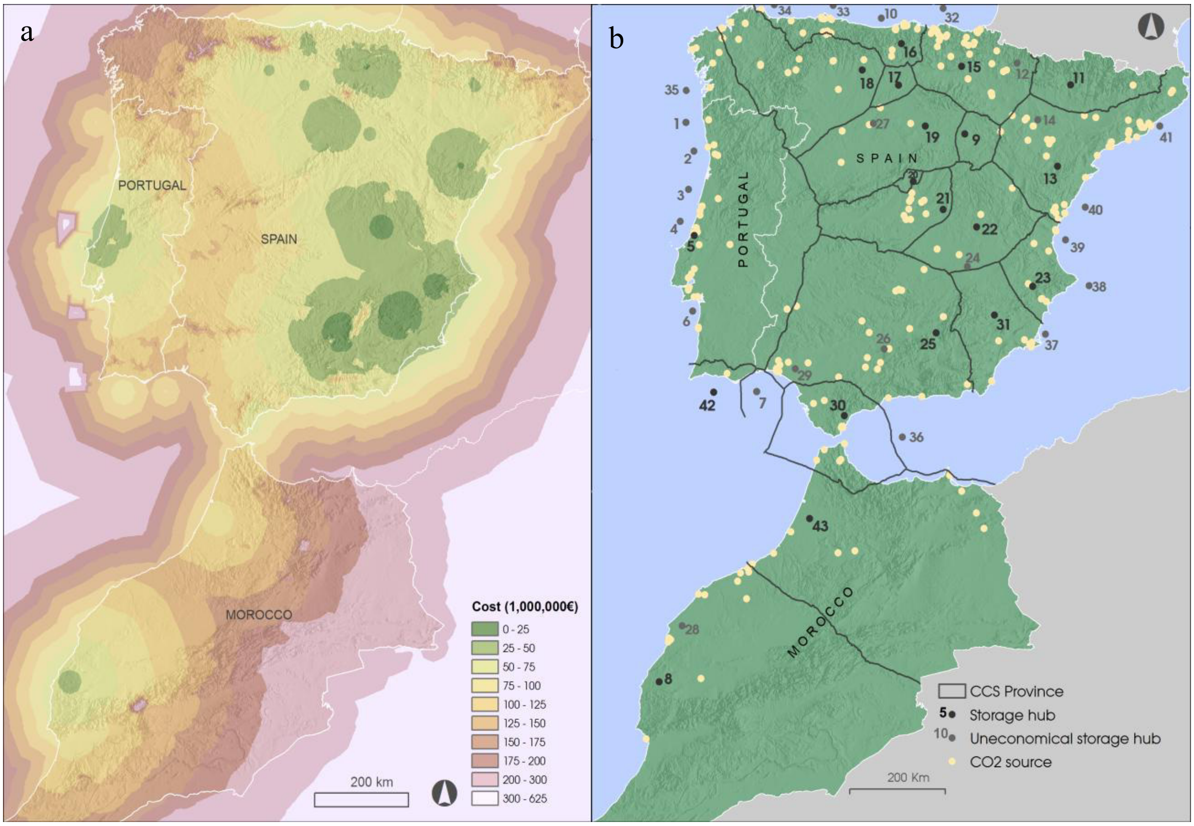

Fig. 5 – a) Integrated cost-distance map for transport and injection of 1Mt/a ; b) CCS Provinces in the study area. Black dots refer to the hypothetical injection site, coinciding with an existing borehole or the centroid of the polygon defining the storage cluster. The number associated to the injection site identifies the CCS province in the text. Grey dots refer (and numbers) to storage clusters that do not define CCS Provinces.

3.4. Results

The cost-distance map in Fig. 5a indicates the largest costs for CO_2 transport and storage for existing or future facilities located at the eastern and northern border between Portugal and Spain, and at the eastern border of Morocco, while the lowest costs are found in central and SE Spain, where there are many potential storage sites.

Morocco encompasses three Provinces, one in the south and SW, centred in the Essaouira sedimentary basin (S8), a second one centered in the Gharb basin (S43), cost-effective for storage of CO_2 from sources in central and north Morocco, and a third Province (S30) dominated by a onshore storage site in the south of Spain that is cost-effective for sources in the Tangier region of Morocco, despite the costs for crossing the Mediterranean.

Despite the 34 clusters defined in Spain, Spain encompasses only 16 CCS Provinces, including the Portuguese S05 Province which is cost-effective for sources located in NW Spain. Thus, 18 clusters in Spain are not cost-effective even for nearby CO_2 sources, due to the large storage costs. All Spanish Provinces are for onshore sites, but some of them (S09, S17, S20) are very small and interesting only for nearby sources, although S20 is very sensitive to storage costs and requires further characterization. The Provinces S13 and S15, in the Ebro Basin, S18 and S19, in the Duero Basin, and S25 in the Guadalquivir basin are the dominating ones, where characterization efforts should focus, and planning integrated transport and storage infrastructures may be most successful.

Portugal is essentially within two Provinces corresponding to the only onshore storage cluster (S05) and to an offshore cluster in the Algarve basin (S42). All main CO_2 sources in Portugal are included in the S05 Province, and as long as the volume of CO_2 is below the annual injection rate at S05, CO_2 captured at those sources should be stored in this cluster. Only in the Algarve an offshore CCS region develops, centered on cluster S42 that is costs competitive for transport and storage of CO_2 from sources located in the Algarve. In a scenario of offshore storage only, Cluster S03, in the north Lusitanian basin, is the best option for storing CO_2 from sources located around Porto and in the central part of the country, including Lisbon.

Investments in reservoir characterization should be directed towards the onshore storage site S05 and to the offshore site S01 and S03, those that can be cost effective under certain scenarios. Interestingly, the storage site in the Sines basin (S06) located just offshore from the largest emissions sources in Portugal, is never cost competitive, due to the large depth and low permeability of the reservoir. The Algarve cluster S42, despite being cost effective for the south of Portugal, is probably not worth studying in detail, because the number of existing sources in its area of influence is very small (currently limited to one cement factory that is reaching its lifetime limit).

CCS ready facilities should preferentially be set within the coastal region of Portugal, along the axis Peniche-Aveiro, where the cost of CO_2 transport and storage to clusters S05 and S03 are smaller. The NE region of Portugal would imply the largest CO_2 transport and storage costs for CCS ready facilities.

4. Conclusions

CO_2 storage costs are dependent on site conditions, including variables such as depth of reservoir, injection rate, onshore/offshore location. Transport costs are also dependent on geographical conditions, such as topography, crossing of water bodies, etc.. The definition of CCS Provinces integrates these two components in a Geographical Information System (GIS) and aims to find the region where a CO_2 storage site is cost-effective based on the cumulative transport and storage costs. The methodology for defining the provinces was illustrated for the Iberian Peninsula and Morocco.

As a first step, the methodology implements a linear cost model for pipeline construction considering local conditions that affect the pipeline cost, such as land-use, ground slope, crossings of infrastructures or other criteria thought adequate for a particular region. Multi-criteria analysis with those local factors, allows building cost surface maps representing the cost of a standardized diameter pipeline in any cell of the GIS model. For each potential CO_2 storage site, investment and OMM costs are estimated on the basis of location (onshore/offshore), depth, injection rate per well, and the number of wells required to inject the CO_2 volume transported by the standardized diameter pipeline. The storage costs are assigned to the potential injection location and the resulting map is combined through map algebra with the transport cost surface. The integrated cost surface represents the localised (at cell level) cost of transport and storage. The CCS Province is defined by finding for each cell in the GIS the lowest accumulative transport and storage cost and allocating to a given province all the cells that lead to the same storage site.

This concept of CCS Province has multiples usages, namely for:

- Prioritizing areas for further investments on storage site characterization;

- Conducting source-sink matching in large regions based on cost-effectiveness;
- Simplification of the CCS chain optimization analysis and processing requirements by removing elements that are proved uneconomical;
- Assisting in planning and optimizing integrated transport networks between multiple sources and sinks;
- Planning the location of CCS ready facilities, in order to minimize the transport and storage costs;
- Visualization of the transport and storage cost impact for any given facility.

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